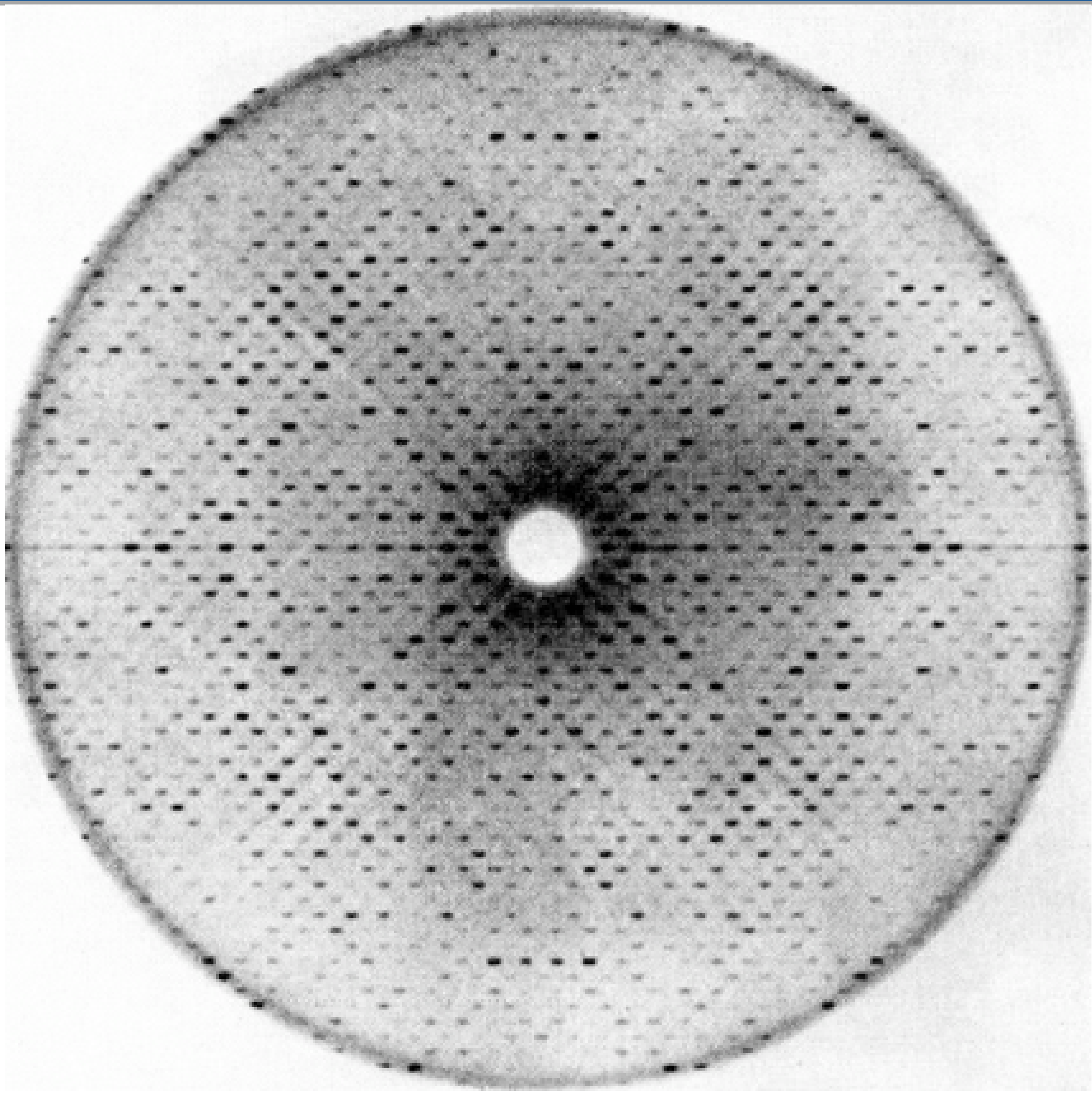
The Coherent Photon Scattering Background



Alan E. Robinson

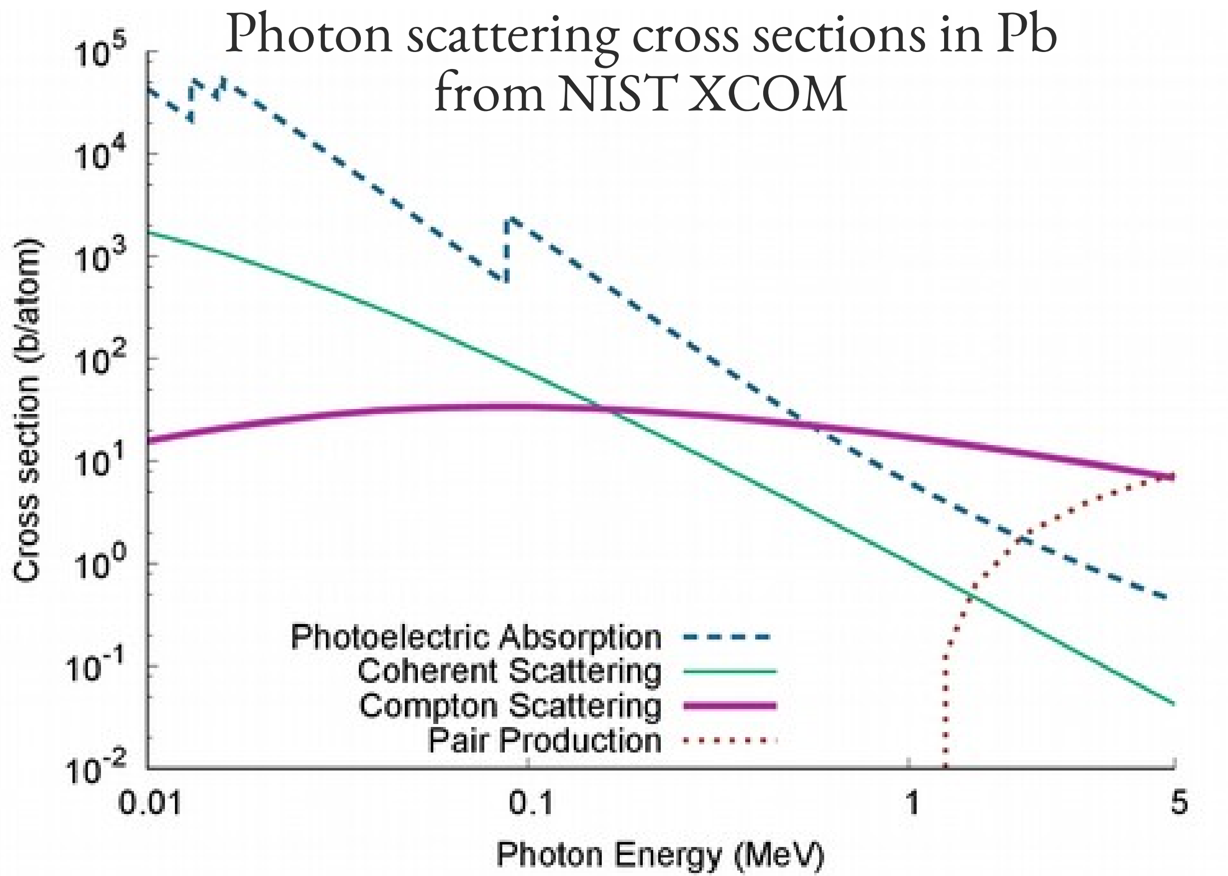
Sub-eV workshop

7 December 2016

Dark Matter Detector Backgrounds

What makes a background troublesome?

- Recoil energy in range of interest
- Indistinguishable from signal
- Difficult to shield
- High rate



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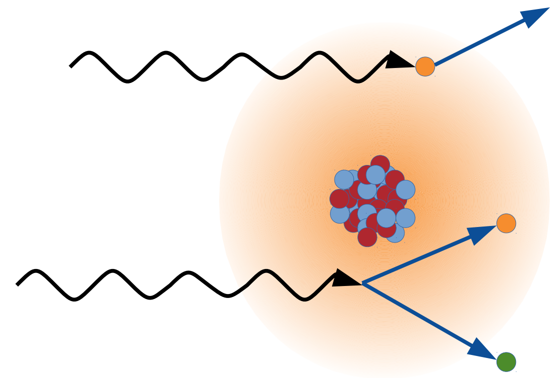
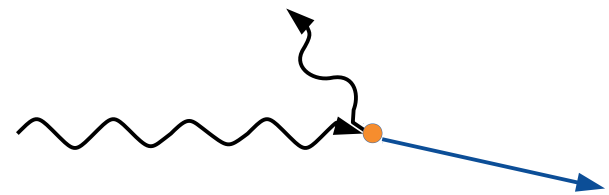
Photon Scattering in Materials

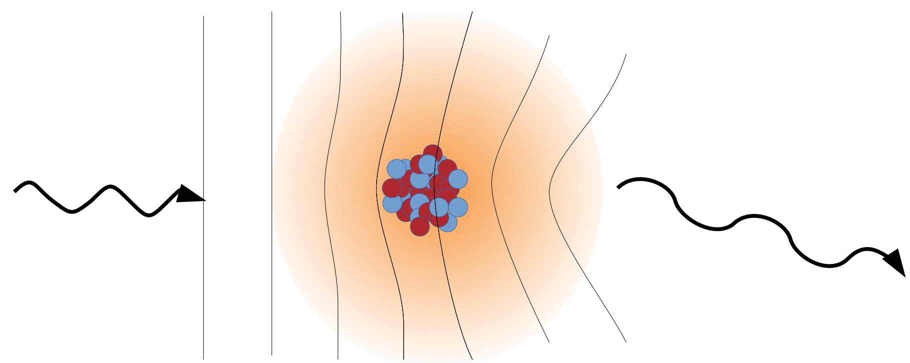
- Deposits full (MeV) photon energy
  - Photoelectric effect
  - Pair-production



- Compton scattering
  - Mitigated by ER/NR discrimination
  - Cut off below electron binding energies (~eV – keV).



- Coherent scattering
  - Changes photon direction
  - Nuclear recoil



Photon Scattering Kinematics

- Non-relativistic recoil energy

$$E_r = \frac{q^2}{2M} = \frac{\left(2 p_\gamma \sin\theta/2\right)^2}{2M}$$

  - With a nucleus

$$E_{r,max} \approx \frac{2\left(1\, MeV/c\right)^2}{100\, GeV/c^2} = 20\, eV$$

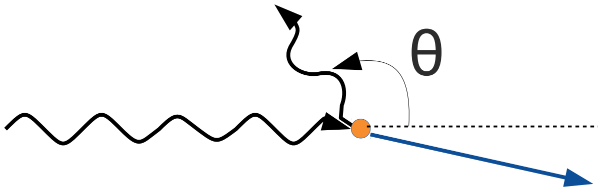
  - With an electron, the (relativistic) Compton edge energy is

$$E_{r,max} \sim E_\gamma$$

Thomson Scattering

Non-relativistic photon scattering from a point charged particle

$$\frac{d\sigma_T}{d\Omega}=\frac{(Ze)^4}{2m^2c^4}\left(1+\cos^2\theta\right)$$



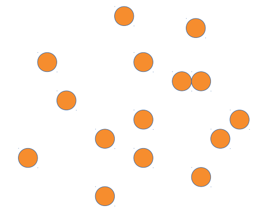
$$\frac{d\sigma_T}{dE_r}=\frac{2\pi M(Ze)^4}{2m^2c^2E_\gamma^2}\left[1+\left(1-E_r M/p_\gamma^2\right)^2\right]$$

M = mass of the recoiling system
m = mass of the interacting particle

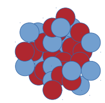
- Applies to low-energy electron and nuclear scattering.

Coherent scattering components

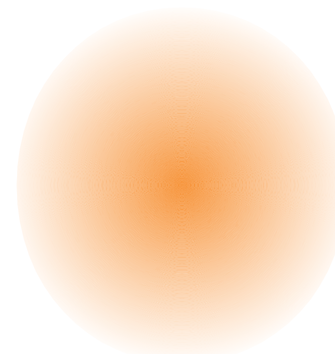
Coherent sum of



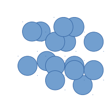
- Rayleigh scattering
  from all electrons



- Nuclear Thomson scattering
  from the nucleus



- Delbrück scattering
  from the vacuum



- Nuclear resonance scattering
  from the protons

Coherent Scattering

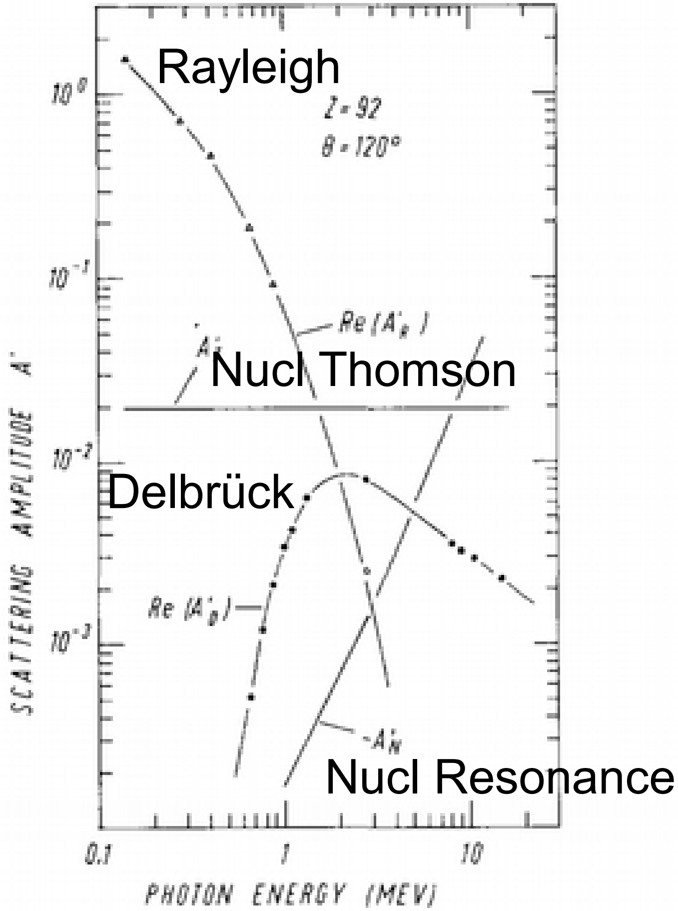


Fig. 1. Real parts of the spin-flip scattering amplitudes A' in units of r_0 (classical electron radius) versus energy, for Delbrück (D), Rayleigh (R), nuclear Thomson (T) and nuclear resonance (N) scattering: △ ref. [14], ● ref. [2], ○ ref. [8].

Phys Lett **71B** 276 (1977)

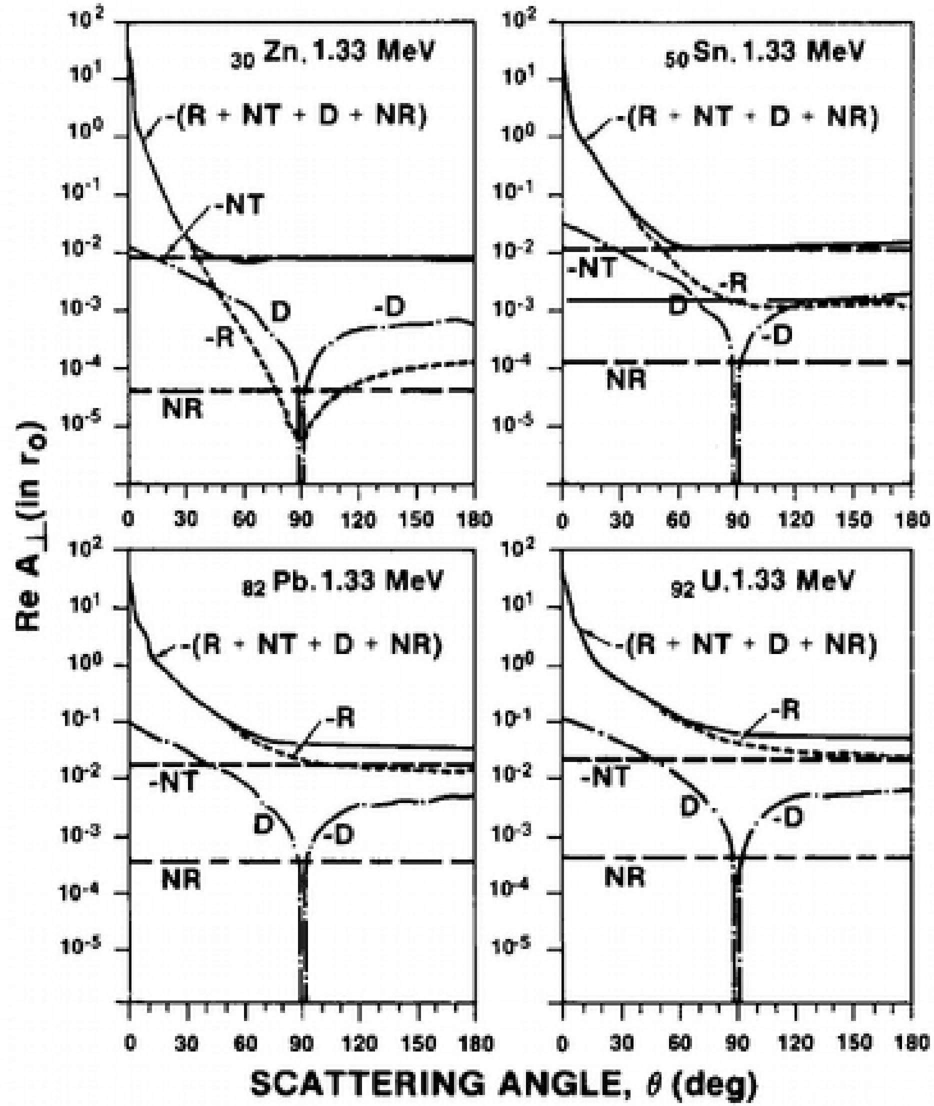


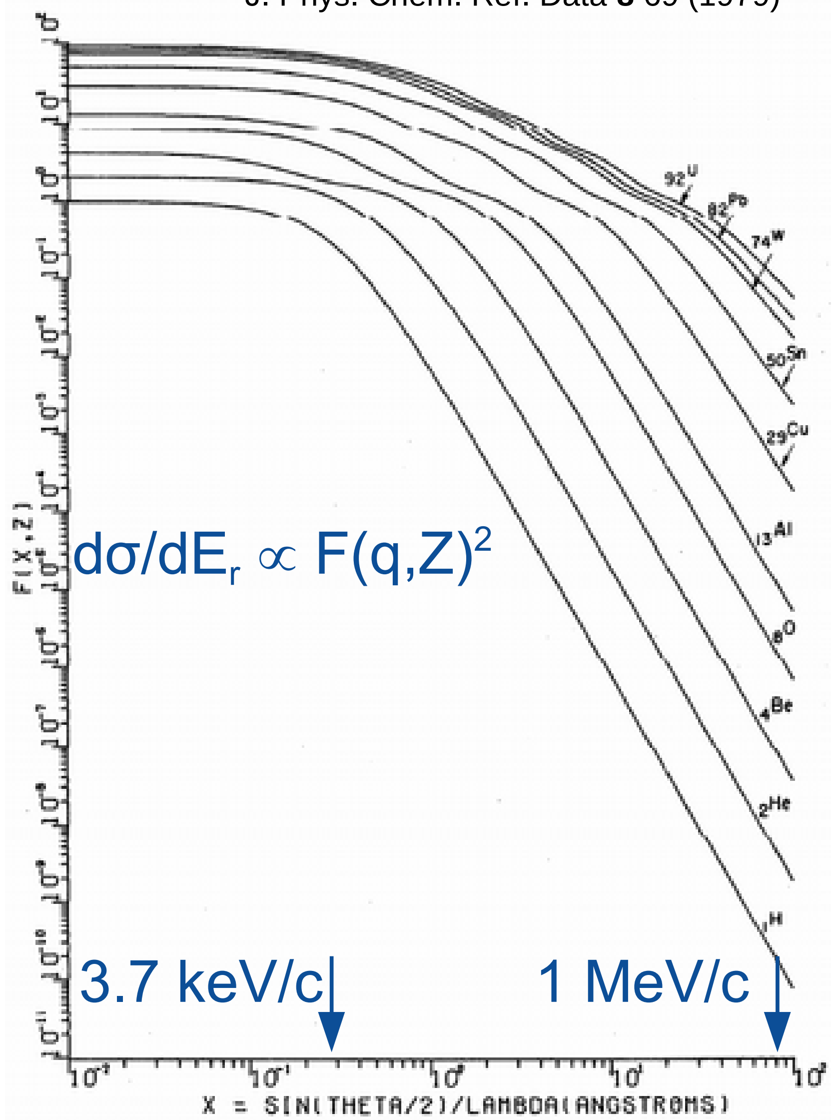
Fig. 2.8. Real scattering amplitudes at 1.33 MeV for various atoms.

Phys Rep **140** 75 (1986)

Atomic Form Factor for Rayleigh Scattering

- Calculations
  - Free atom S-matrix calculations for $Z \geq 13$, $E_\gamma < 1.5$ MeV
    - J. Phys. Chem. Ref. Data **27**, 1011 (1998)
  - Form factor calculations
    - Approximate Delbrück and nuclear resonance terms Available for all Z, E_γ
- Coherent scattering is heavily suppressed for momentum transfers > s-shell e^- momentum
  ($q > \hbar Z/a_B = 3.7$ keV $\cdot$ Z)

J. Phys. Chem. Ref. Data **8** 69 (1979)



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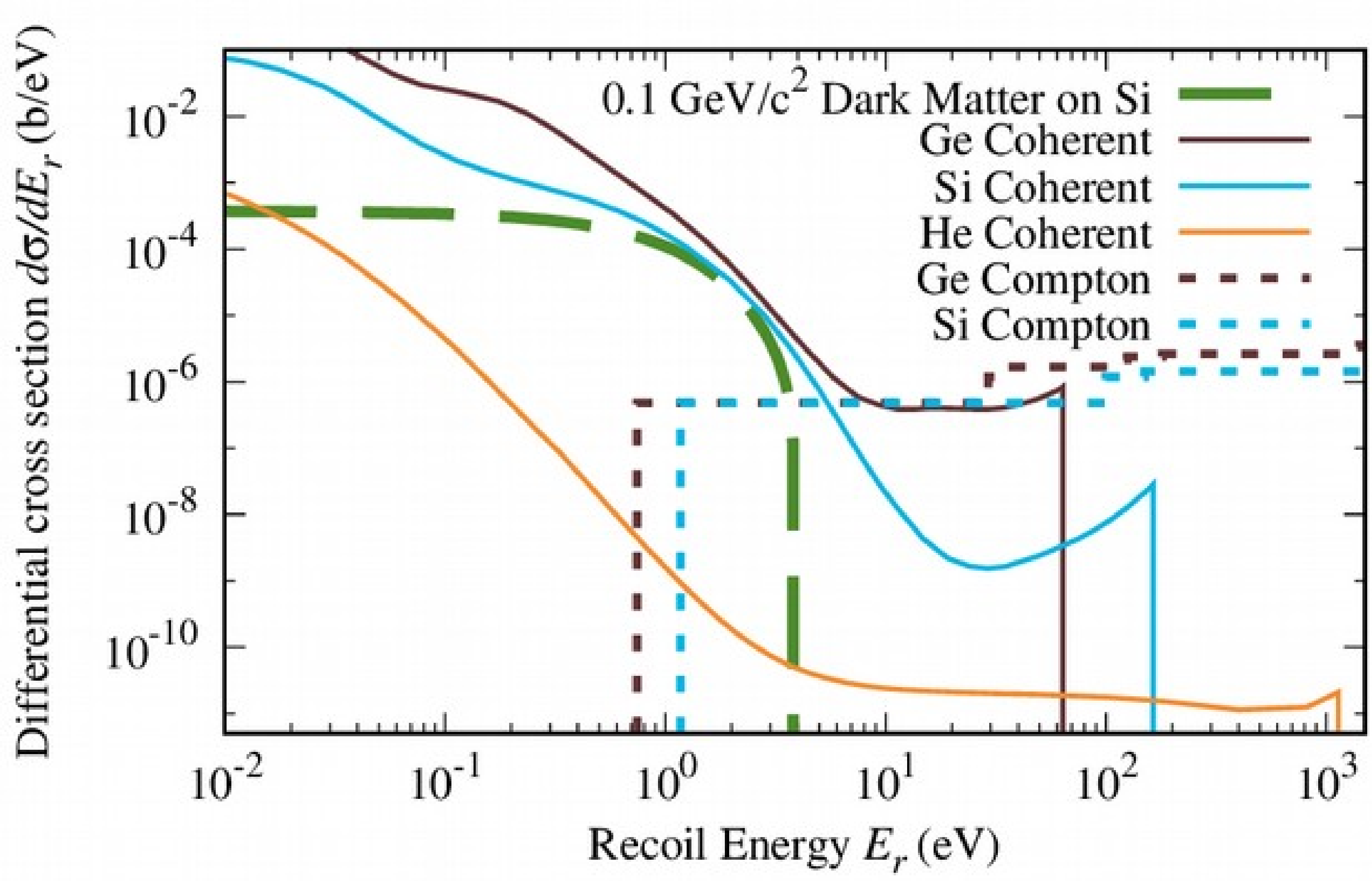
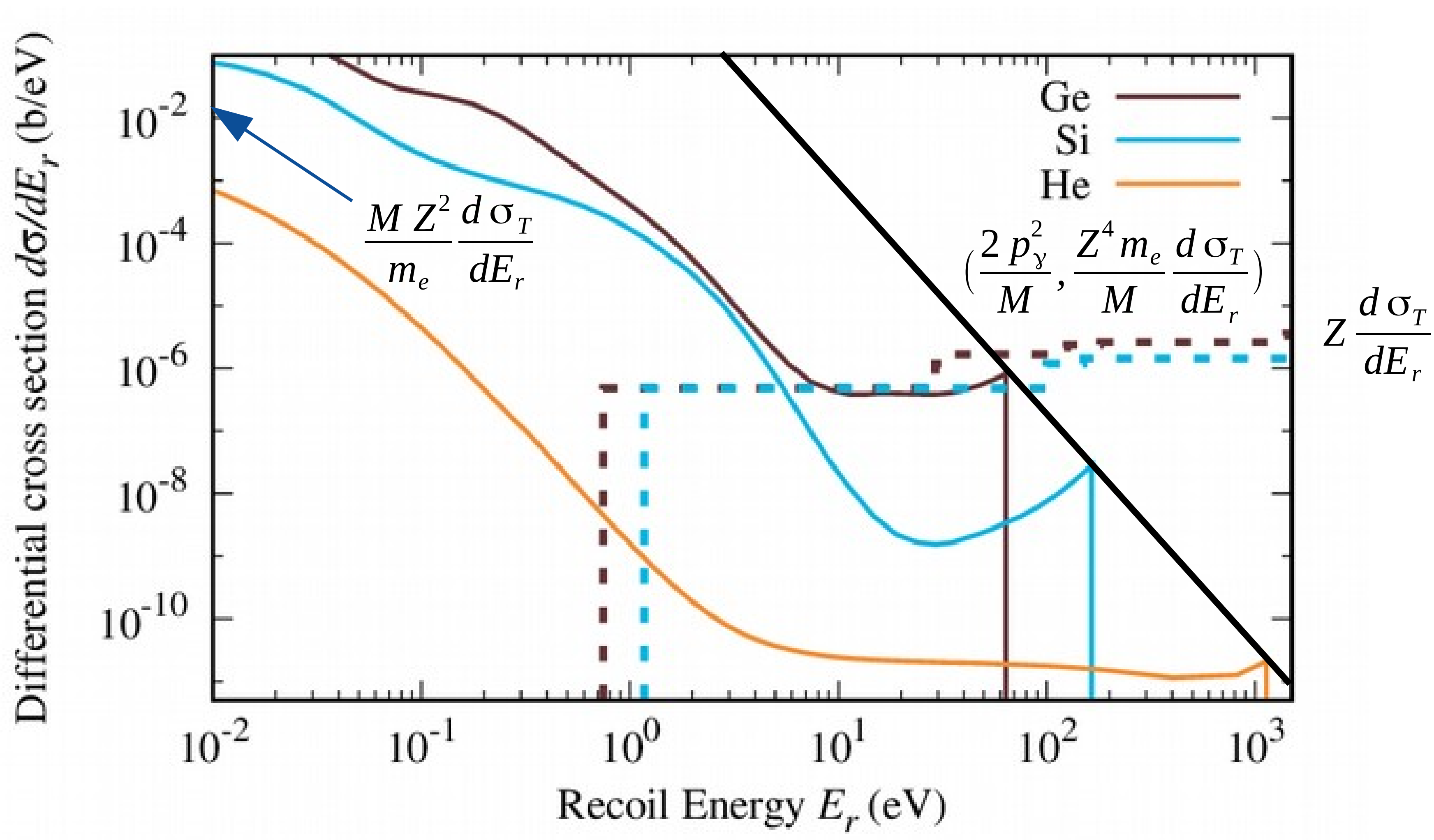
Cross sections for 1.46 MeV photons



Cross sections for 1.46 MeV photons



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Dark Matter Detector Backgrounds

What makes a coherent photon scattering background troublesome?

- Recoil energy in range of interest
  - ✔ eV and sub-eV scale.
- Indistinguishable from signal
  - ✔ Nuclear recoils
- Difficult to shield
  - ✔ Produced by highly penetrating MeV photons
- High rate
  - ✔ Orders of magnitude greater than Compton scattering < 10 eV
  - ✔ Large nuclear recoil background for
    Er < 15 keV / atomic mass (amu)

Coherent Background Rates

Expected coherent scattering background based on 0.04 dru Compton background of 1461 keV photons.

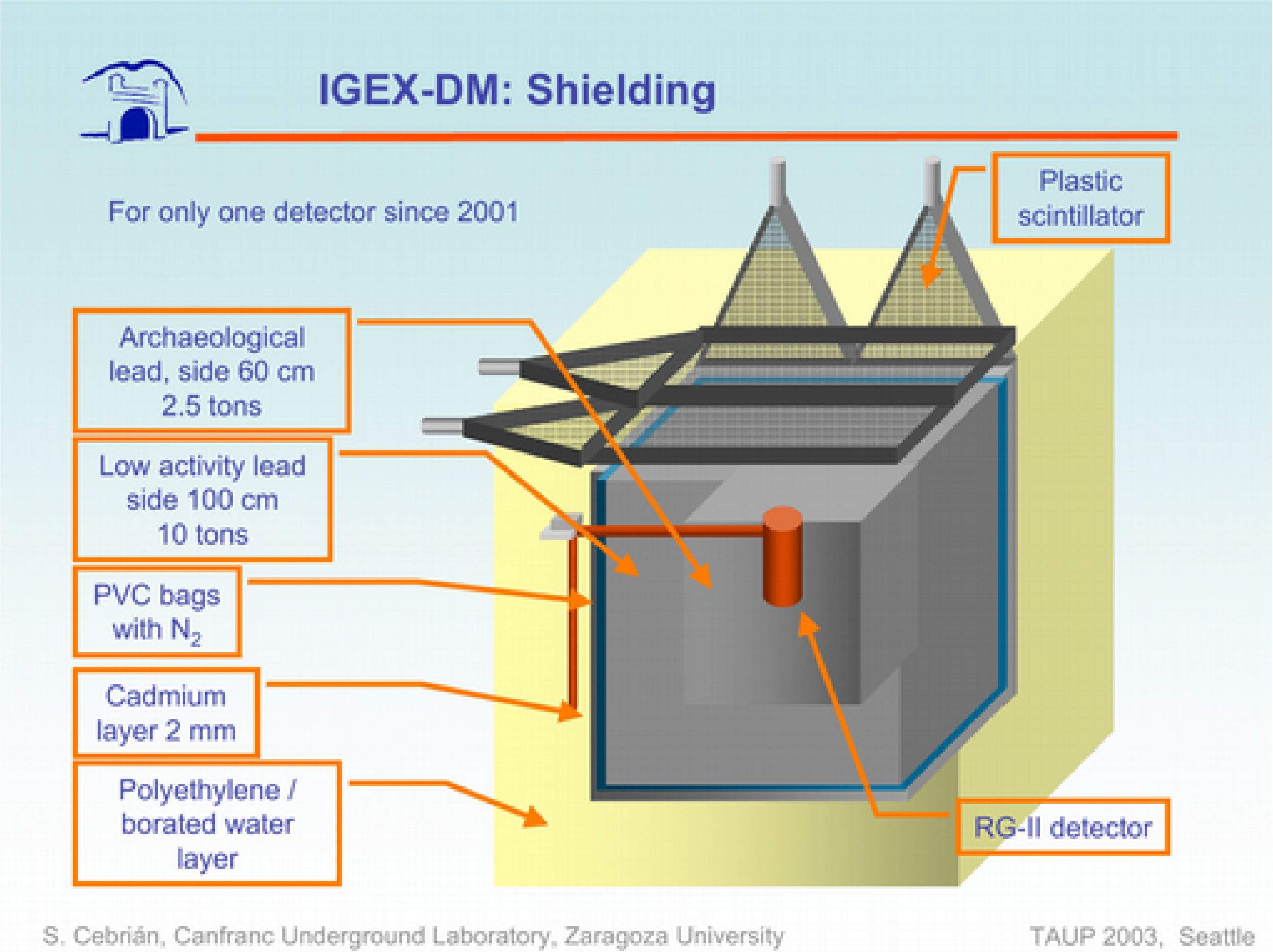
Recoil Energy Range [eV]	Integrated Scattering Rate [recoils $(\mathrm{kg{\cdot}yr})^{-1}$]		
	Ge	Si	He
<0.01	72	16	1.0
0.01–0.1	34	13	0.5
0.1–1	16	5	0.012
1–10	0.8	0.9	6×10^{-5}
>10	0.10	0.012	0.0010

>10 eV recoil rate increases with assumed photon energy.

<10 eV recoil rate is nearly independent of photon energy.

Background Rates

0.04 dru Compton was achieved by IGEX



Effects on proposed experiments

- 0.1 kg-yr background free exposures at not easily achieved for thresholds < 1 eVnr, except in very-low Z materials (e.g. He)
- ER/NR discrimination of photon events is limited below 0.1 – 1 keVnr, depending on target material

Coherent background rate from 1461 keV photons producing 0.04 dru of Compton scatters

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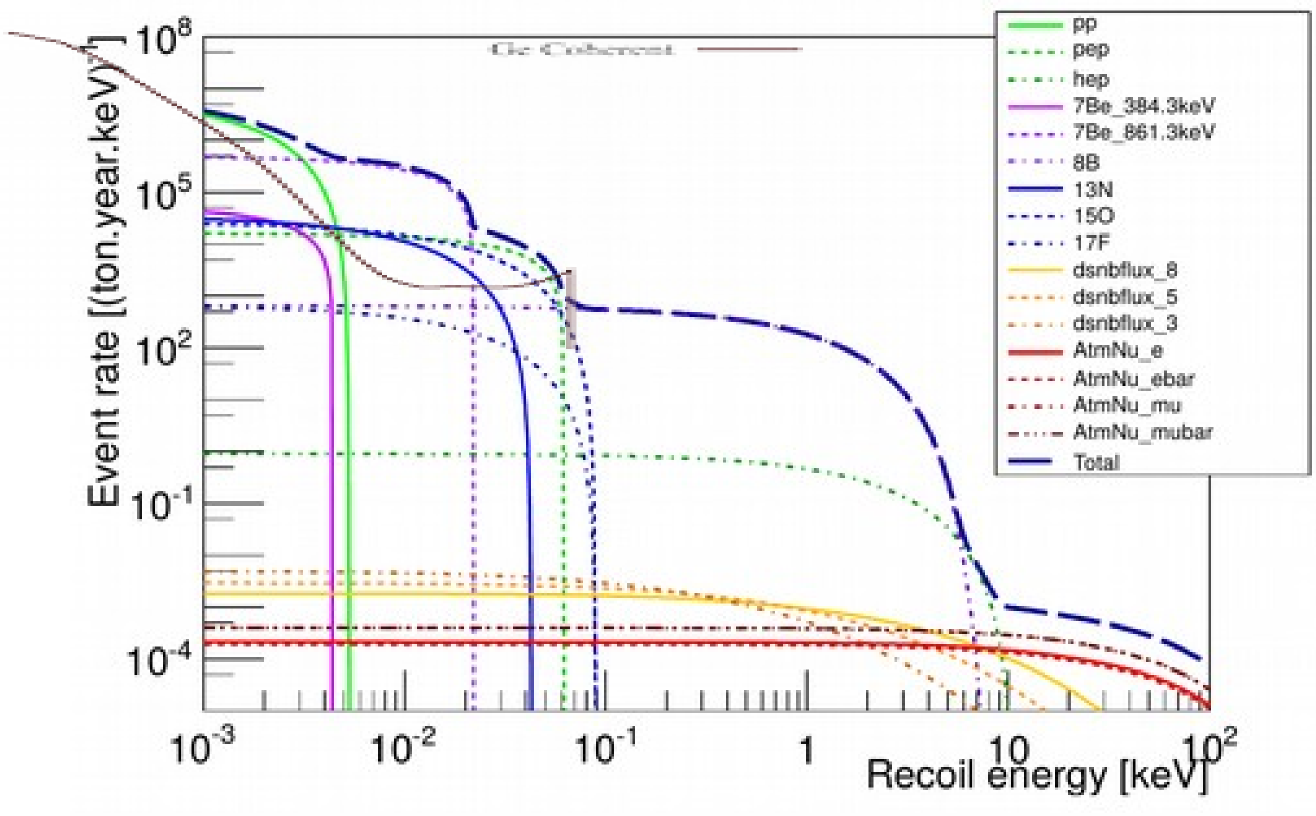
Effects on proposed experiments

Comparison to the coherent neutrino background

- Assuming 1.46 MeV photons with 0.04 dru Compton rate
- Does not account for neutrino-electron coherent scattering



Phys. Rev. D 89, 023524 (2014)

Effects on planned experiments

- SuperCDMS SNOLAB
  - Science reach for phase 1 is unaffected.
    - HV threshold ≥35 eVnr
      - Above coherent turnon at 10 eVnr
      - ^{3}H and surface background leakage exceed nuclear Thomson component
    - iZIP ER/NR discrimination > 1 keVnr
      - Above nuclear Thomson cutoff from 2615 keV photons at 520 eVnr
  - May observe nuclear Thomson scattering during calibrations on Ge HV detectors
    - $Z^3 m_e / M = 0.25$
    - HV gain stretches electron recoil spectrum by a factor ~10.
    - Potential NR energy scale calibration at Thomson cutoff.

Simulating backgrounds

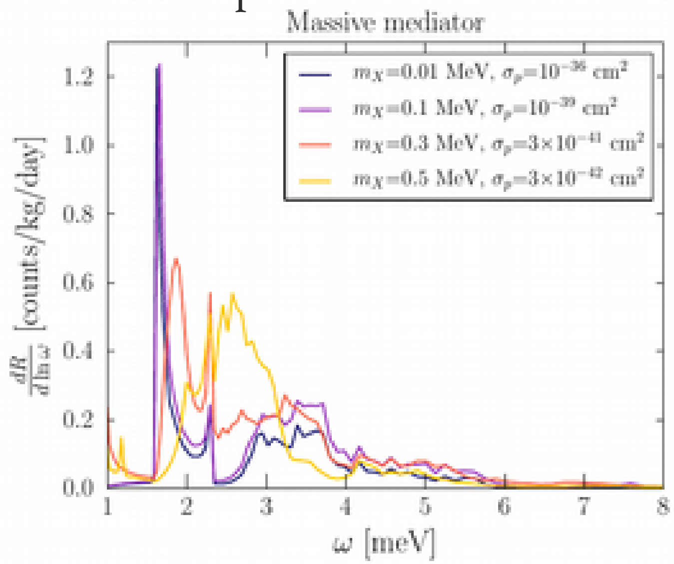
- Coherent scattering is implemented in both Geant4 and MCNP, but energy depositions from coherent scattering are ignored.

An aside: Structure factors

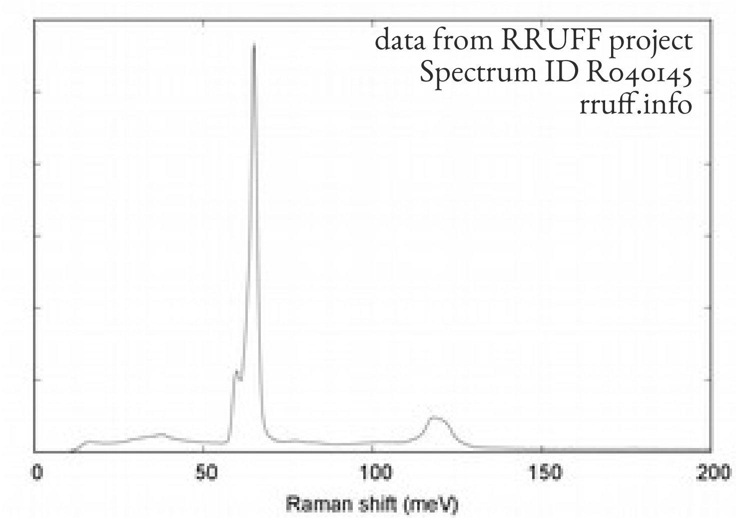
All calculations shown assume scattering from free atoms. Structure effects, (e.g. Bragg scattering), can drastically change interaction probabilities and spectra.

- e.g. S Knapen, T Lin, and KM Zurek, "Light Dark Matter in Superfluid Helium: Detection with Multi-excitation Production," arXiv:1611.06228.

Predicted dark matter scattering spectrum in He-II



Raman scattering spectrum in a Si crystal with unspecified orientation



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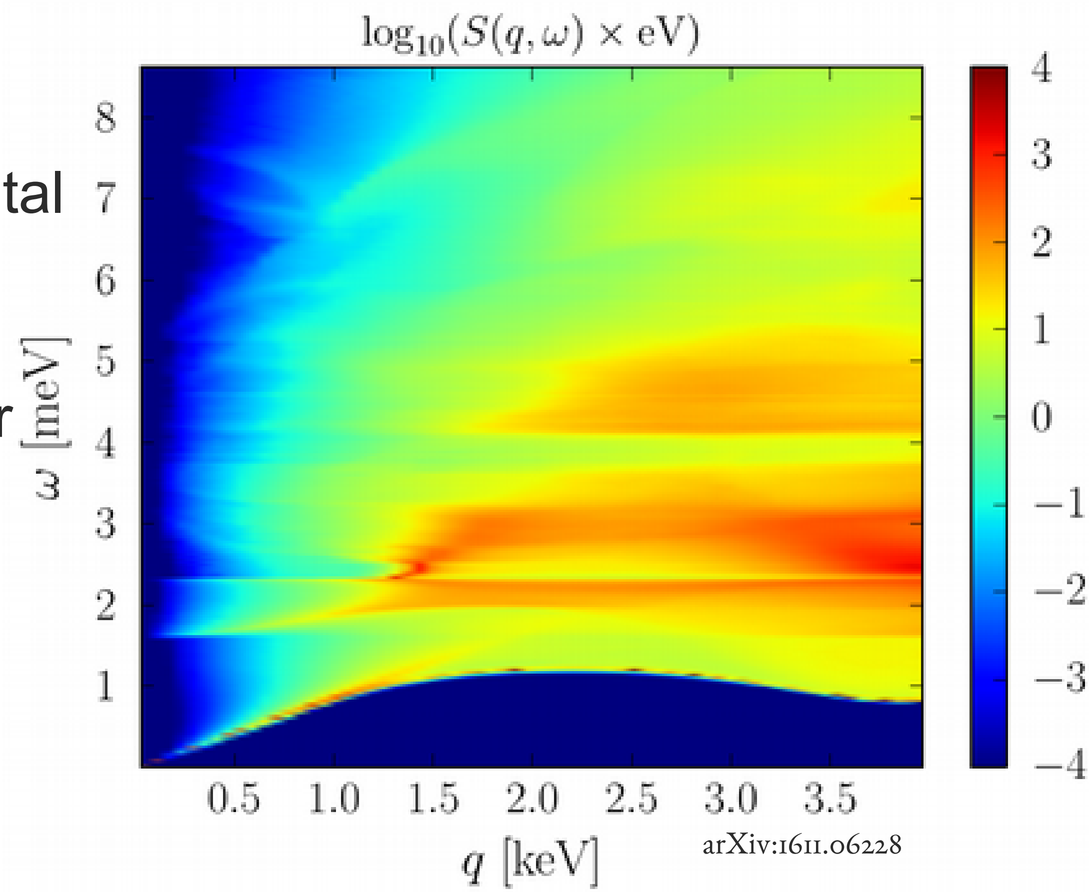
An aside: Structure factors

Structure factor S(**q**,E_r) modifies the free atom differential cross-section

- Bragg interference term in crystals at low-q
  - Recoil from entire crystal
    - $E_r = 0$
  - Bragg intensity given by Debye-Waller factor

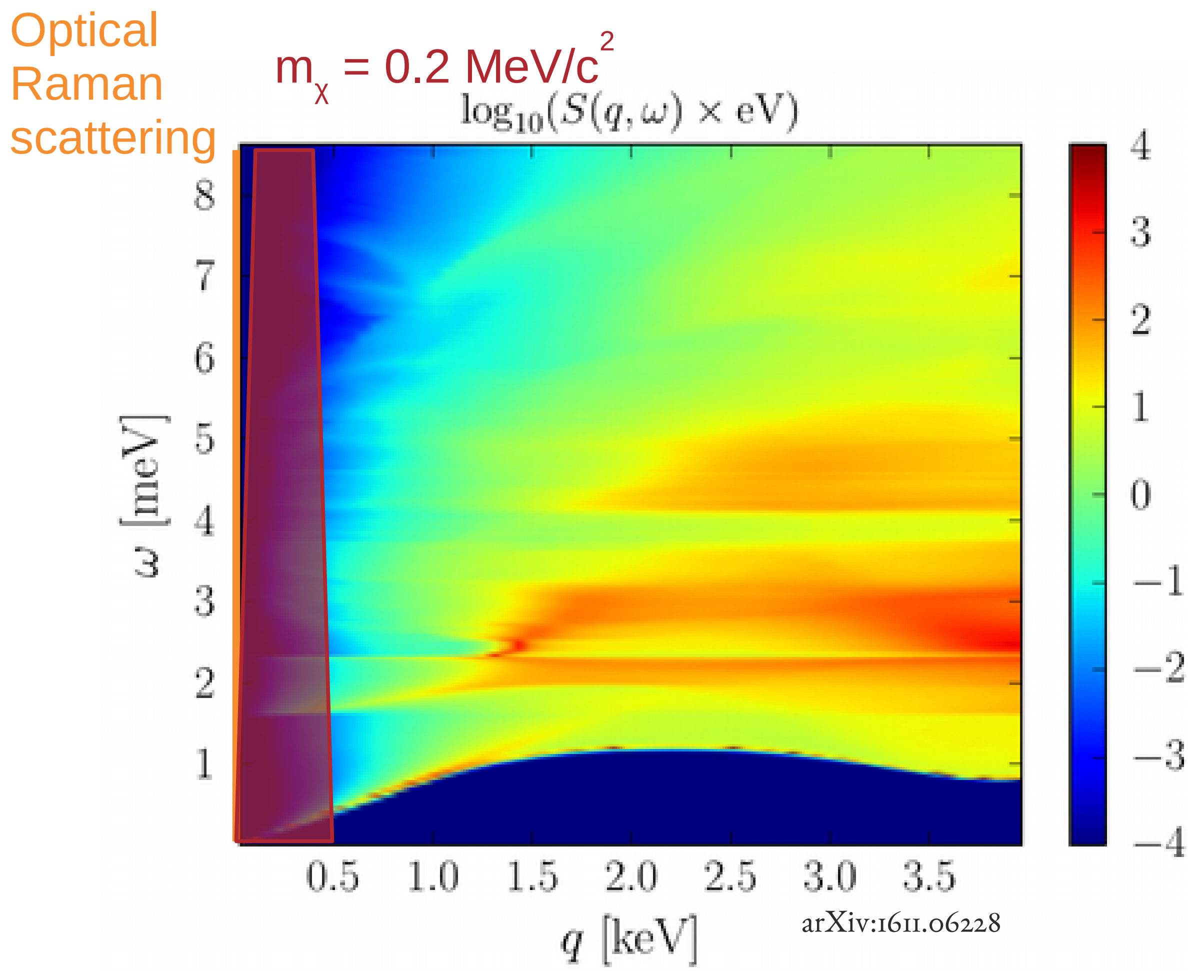
$$\frac{I}{I_o} = \exp\left(\frac{-q^2}{2M}\frac{\langle U \rangle}{\langle U_o \rangle^2}\right) \sim \exp\left(\frac{-E_r}{0.02\,eV}\right)$$



arXiv:1611.06228

An aside: Structure factors

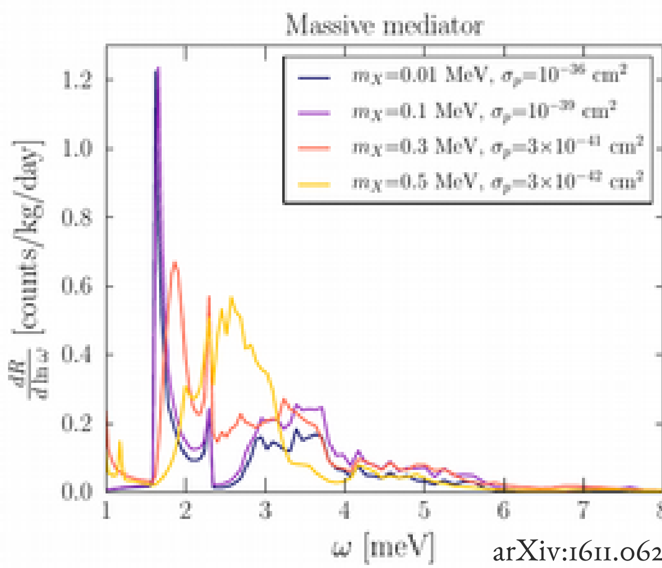
Integrate $S(\mathbf{q},E_r)$ over accesible values of **q** to get spectrum.



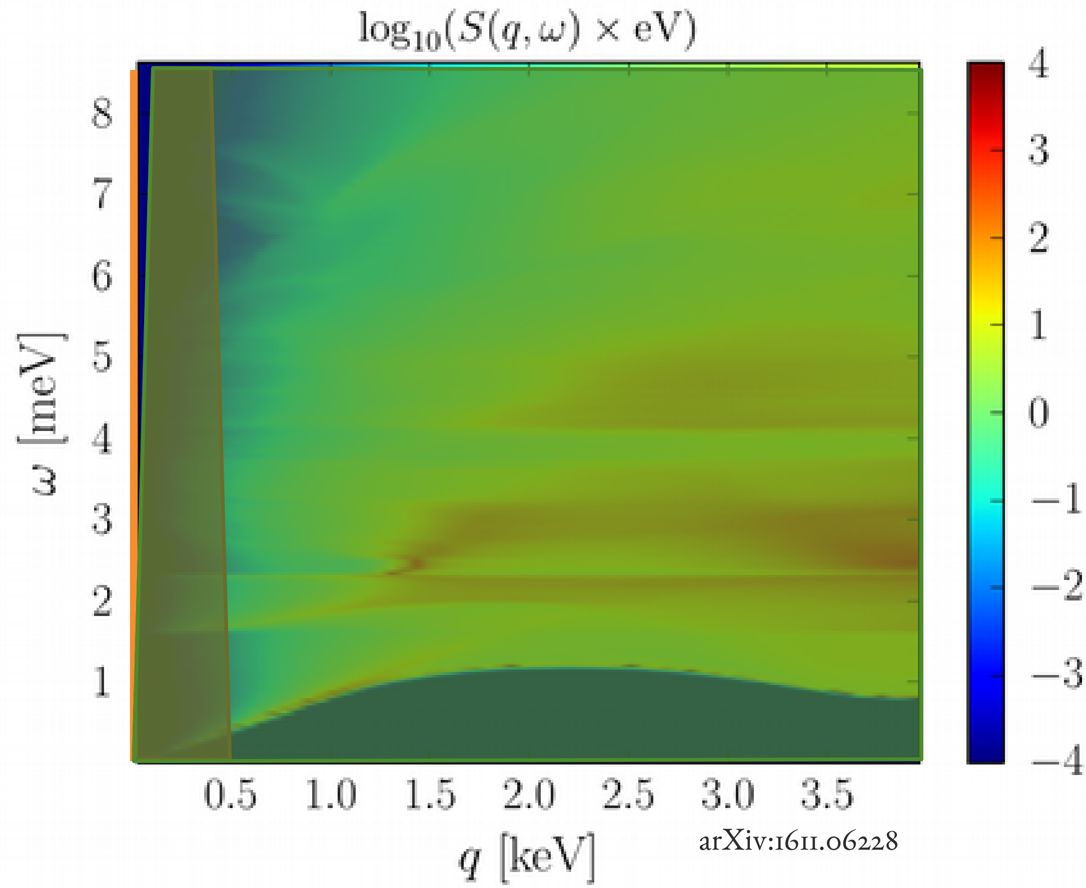
An aside: Structure factors

MeV photons (& heavy DM) have large accessible phase space.

- Peaks in spectrum are smoothed out.



arXiv:1611.06228



arXiv:1611.06228

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An aside: Structure factors

- Are differential rates enhanced or suppressed by collective effects?
  - Yes
- At what energies do collective effects become important?
  - $\lesssim 0.01 – 0.1$ eV
- Can collective effects help distinguish dark matter scattering from photon scattering?
  - Possibly for light dark matter.
    - Requires a dark matter signal at a minimum in the photon scattering background.
    - Structure factors are integrated over a wider phase space for MeV scale photons that includes the phase space of dark matter recoils, so that there will always be some background.

Conclusion

Coherent photon scattering is an important and well understood radioactive background for sub-eV nuclear recoil calorimeters

- Scales with low-energy Compton spectrum
- Proportional to ~Z^3

Coherent background rate from 1461 keV photons producing 0.04 dru of Compton scatters

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Extra Slides

Low-energy Compton Background Rates

Typical experiments (dru = counts/kg/day/keV)

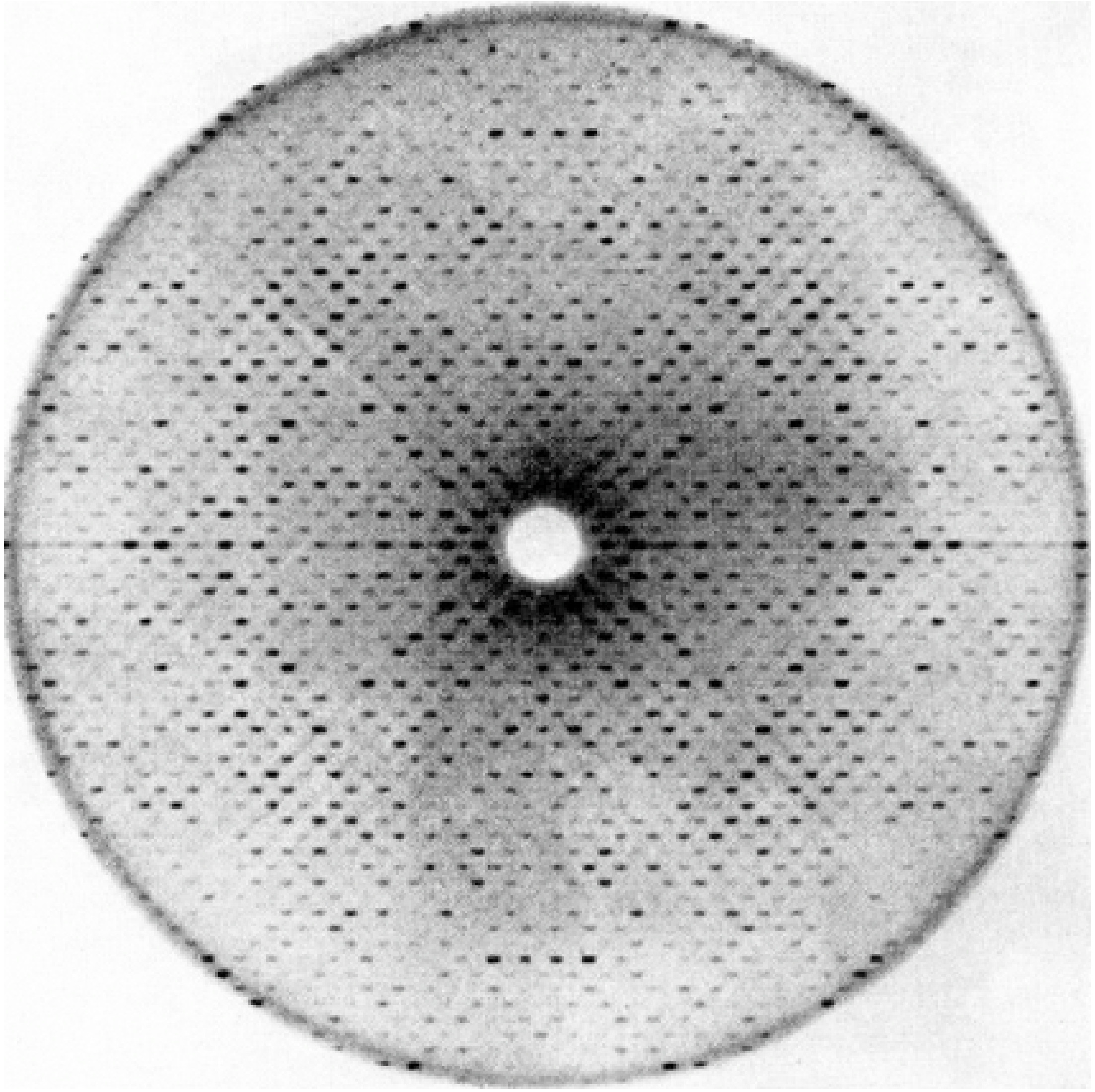
- **IGEX: 0.04 dru measured** S. Cebrian, TAUP 2003
- CoGeNT: <1.7 dru measured (incl. ^{3}H) PRD **88** 012002
- SuperCDMS SNOLAB: 0.03 dru goal arXiv:1610.00006

Underground test facilities ~10 – 100 dru

State-of-the-art experiments

- Majorana Demonstrator: 0.006 dru estimated arXiv:1610.01146
- LUX (self-shielded): 0.0018 dru modeled arXiv:1310.8214

Cover Photo



Bragg scattering from CuZn

J.S. Richardson Duke University

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